The Dependence of Nadir Ocean Surface Emissivity on Wind Vector as Measured With Microwave Radiometer

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***Abstract*—Global brightness temperature observations of TOPEX/Poseidon microwave radiometer (TMR) at 18, 21, and 37 GHz have been collocated with near-simultaneous SeaWinds wind vector data as well as with monthly sea surface temperature and salinity products. The combined data allow us to study the dependence of zenith-directed ocean surface emissivity, at each frequency, upon both wind speed and direction. Results show a clear two-branch wind speed dependence; weak and linear below 7 m·s^{-1} with an increase in sensitivity above that point. The observed emissivity also depends on the angle between the wind direction and TMR's antenna polarization orientation, providing satellite confirmation of aircraft-derived results. There is little change in these wind vector dependencies with frequency.**

***Index Terms*—Nadir ocean surface emissivity, SeaWinds wind vector, TOPEX/Poseidon microwave radiometer (TMR).**

I. Introduction

The TOPEX/Poseidon microwave radiometer (TMR) is a three-frequency radiometer operating on the TOPEX/Poseidon (T/P) satellite. It measures radiometric brightness at 18, 21, and 37 GHz in a nadir-viewing direction co-aligned with T/P radar altimeters [1]. Its primary objective is to monitor and correct for the propagation path delay of the Ku-band altimeter signal due to atmospheric water vapor and cloud liquid water [2]. For TMR, this wet tropospheric path delay is derived from the three-frequency brightness temperatures T_b as discussed in [3]. Delay is highly variable in space and time and, if uncorrected, leads to altimeter range measurement errors of 3–45 cm. TMR is designed to provide this range correction with 1.2 cm accuracy.

Most satellite altimeters are now supported by a two- or three-frequency water vapor radiometer. One issue in designing these systems is compensation for the second-order brightness temperature variations associated with changing ocean surface emission. While the wind speed dependence of zenith-directed emission is fairly well known and already characterized within path delay algorithms, it has also been shown [4] that there should be a small ΔT_b associated with wind direction change. This sensitivity comes from the fact that the thermal emission from anisotropic sea waves depends upon azimuthal (polarization at nadir) observation angle.

Several experimental studies have addressed this sensitivity to the wind vector by means of circle flights [4]–[8]. These aircraft measurements indicate a direction detection capability for nadir-looking systems as well as a potential error source for spaceborne water vapor radiometers (such as TMR) aboard altimeter platforms. Reported measurements and theoretical investigations [9]–[11] suggest that the nadir-looking radiometer directional sensitivity follows from the azimuthal anisotropy of the spatial spectrum of short-gravity and capillary waves.

The aim of this communication is to use satellite data from the TMR to document the impact of wind speed and direction on surface emissivity at 18, 21, and 37 GHz. To the authors' knowledge, the study presents the first on-orbit evidence of a wind direction dependence at nadir. This work follows similar efforts focused on the off-nadir pointing spaceborne Special Sensor Microwave/Imager (SSM/I) deployed on the Defense Meteorological Satellite Program (DMSP) missions [12], [13]. The approach is simply to observe ΔT_b variation versus the angle between TMR's linear polarization alignment and the surface wind direction. To this end, a large global data set has been compiled by combining scatterometer (SeaWinds) wind vector measurements with T/P observations at satellite crossover points over a year-long period. The extensive data set carries a broad coverage of environmental conditions and permits robust removal of the first-order atmospheric signal needed to isolate the surface emission signals with certainty. In Section II, we recall Giampaolo and Ruf's [14] approach for TMR emissivity estimation using quantities that can either be obtained directly from satellite measurements or approximated from ancillary sources with satisfactory accuracy. Section III describes the large global compilation of TMR, SeaWinds wind vector, the monthly sea surface temperature (T_s) climatological estimates, and the climatological sea surface salinity (SSS) product used in this study. Sections IV and V present, respectively, wind speed and wind direction dependencies of the sea surface emissivity as measured with TMR. Section VI provides conclusions.

VI. Conclusion

Observations presented in Sections IV and V serve to document the zenith-directed wind-induced ocean emissivity ($\Delta\epsilon$) at 18, 21, and

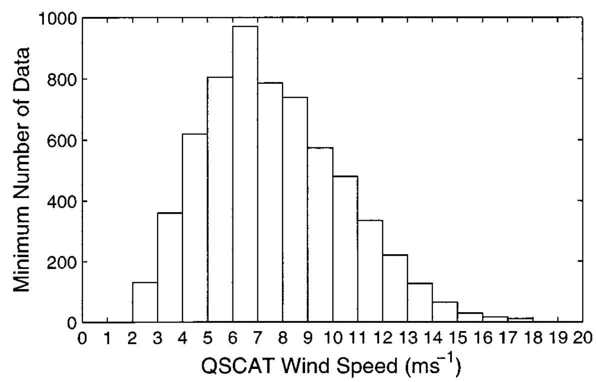

Fig. 7. Minimum number of data in a 30° azimuth angle bin for each 1 m·s^{-1} SeaWinds/QSCAT wind speed interval.

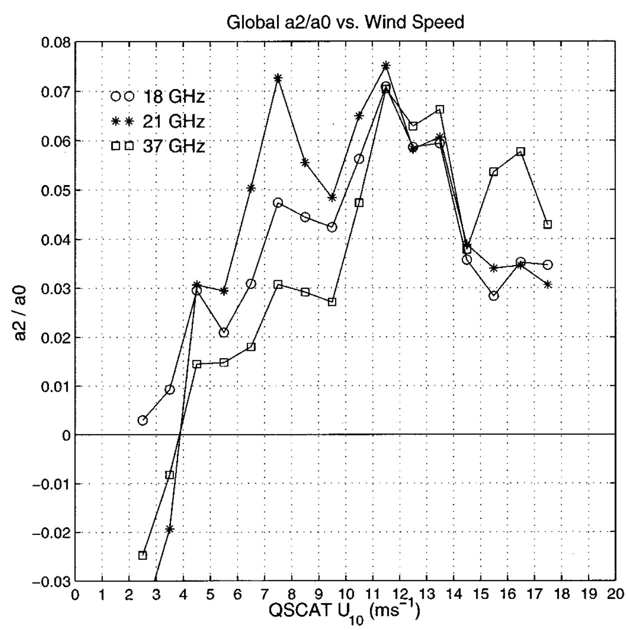

Fig. 8. Dependence of the normalized second-order harmonic $a2/a0$ on SeaWinds/QSCAT wind speed.

37 GHz. These data come from a carefully filtered combination of TOPEX radiometer and SeaWinds scatterometer data, augmented by surface temperature and salinity estimates. The nadir-detected satellite brightness temperature is shown to depend on both wind speed and direction. This study represents the first satellite confirmation of a directional sensitivity at nadir.

The data show a clear two-branch wind speed dependence; weak and linear below 7 $\mathrm{m \cdot s^{-1}}$ with an abrupt increase in sensitivity above that point for all TMR three frequencies. The $\Delta\epsilon$ is a factor of two to three higher above 7 $\mathrm{m \cdot s^{-1}}$. As mentioned, the microwave emission exhibits a smaller, but measurable, dependence on wind direction. This signal is attributed to the polarized nature of the surface wave structure. The peak-to-peak brightness temperature directional signal is of the order of 1.0 K at 11.5 $\mathrm{m \cdot s^{-1}}$. Observations vary little with frequency versus wind speed or direction. These global-average results are the product of a large data compilation and low regression uncertainties. Agreement with previous aircraft and SSM/I studies suggest high confidence in the findings.

These results are applicable in several areas. First, the data confirm the potential for a nadir-viewing wind direction sensor. Such a sensor would necessarily be a polarimetric radiometer in order to isolate the polarized emission from the largely unpolarized background signal. The globally-derived observations should also serve to complement the results derived from aircraft case studies, where all measurements are being assimilated into ocean emission models [8], [34]. Finally, the accuracy of the water vapor radiometer's altimeter path delay correction can be reassessed based on the present observations. As discussed in [35], the two frequency systems are most susceptable to an additional frequency-independent error source (such as $\Delta\epsilon$ dependence on direction). For example, the GEOSAT-follow-on (GFO) or ERS radiometers operate near 22 and 37 GHz. A first-order estimate suggests that a 0.20 cm wet path delay error (and hence sea level error) will result from a peak-to-peak directional T_b variation of 1.2 K at both 22 and 37 GHz. While this level is certainly small, ocean basins can systematically differ in their mean wind directions. Therefore, the error is not necessarily random.

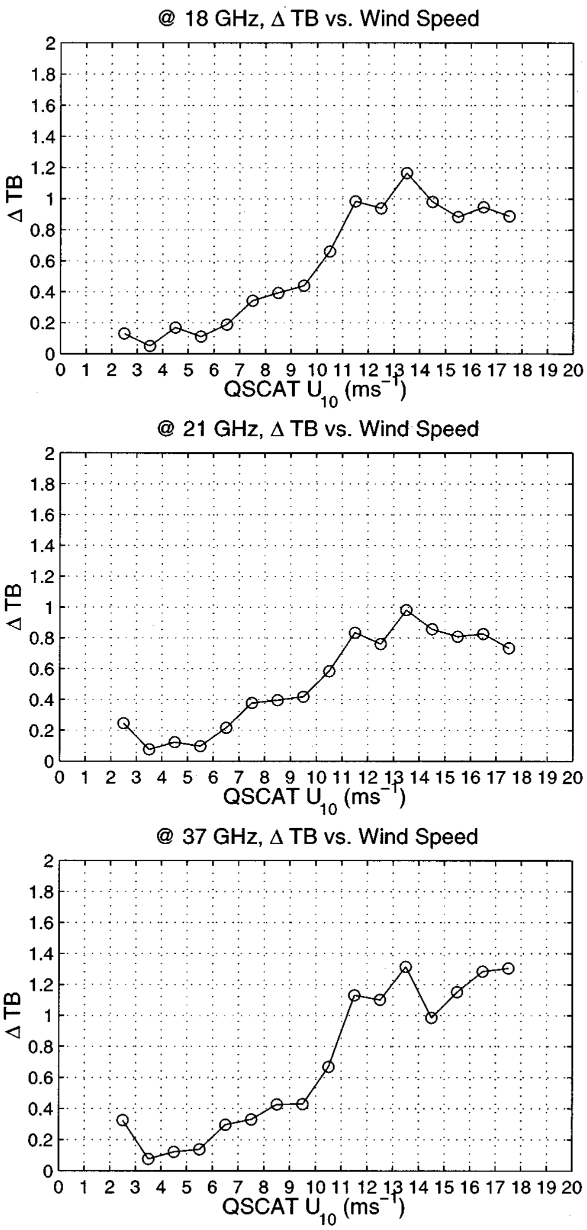

Fig. 9. Amplitude of the directional signal in term of peak-to-peak brightness temperature as a function of SeaWinds/QSCAT wind speed for the three frequencies.